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EXPERIMENTAL INVESTIGATION OF CONDENSER PRESSURE CONTROL DURING SNAP-8 STARTUP

II - Deadband Flow Control of Condensing Pressure

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16. Abstract

A critical area of concern in the startup of the SNAP-8 system to the self-sustaining level is the controllability of the condenser inlet static pressure. A deadband condenser inlet pressure control method was applied to a SNAP-8 system in a ground test facility. This control method, wherein condenser inlet pressure excursions outside the deadband limits resulted in ramp changes in flow of the condenser coolant, was used successfully during a large number of start tests of the system. Parameters that could be manipulated in optimizing this control method were investigated. The influence of outside disturbances on operation of the control was also noted.

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SUMMARY

Tests were conducted on a SNAP-8 test system at Lewis Research Center to evaluate the proposed procedures for startup and shutdown of the SNAP-8 system in space. These tests consisted of 135 startups and shutdowns of the mercury Rankine power conversion system. One of the critical parameters during startup is the condenser inlet pressure. High pressures must be prevented to avoid lowering the turbine output power, and low pressures must be avoided to prevent the mercury pump from cavitating. A deadband method for controlling this pressure was investigated as part of the test program. With this method the pressure is controlled by varying the condenser coolant flow rate whenever the pressure goes outside a predetermined deadband.

The control capability was tested for various control parameters and outside disturbances. For the initial startup ramp in mercury flow up to the self-sustaining level, the deadband condenser inlet pressure control performed satisfactorily over a wide range of conditions in the one-g test environment. However, in a zero-g environment with no liquid head pressure available at the pump inlet, pump cavitation would have resulted for some of the operating conditions tested. For some values of the control parameters tested, condenser inlet pressure response was oscillatory requiring frequent movement of the valve though pressure was maintained approximately within the deadband. Also, one case was found for which the condenser inlet pressure rose high enough to cause a dip in turbine speed at the self-sustaining level of operation. Control parameter values which yielded satisfactory control for given disturbances are given. Also discussed are acceptable ranges for condenser disturbances.

The data indicated significant amounts of vapor pressure drop for small condensate inventories. In order to maintain positive control of pump inlet pressure at all times the condenser inventory should not be less than about 30 pounds (14 kg).

INTRODUCTION

SNAP-8 is a nuclear-Rankine-cycle space power system currently under development (ref. 1). It has liquid metal heat-transfer loops. A eutectic mixture of sodium and potassium (NaK) is circulated to transfer heat from the nuclear reactor to the mercury boiler. In the mercury Rankine loop, subcooled mercury is preheated, evaporated, and superheated in a counterflow multitube boiler. After passing through the turboalternator, the mercury is condensed and subcooled in a counterflow multitube condenser. The heat rejection loop circulates NaK to transfer heat from the condenser to the radiator where it is dissipated to space. This electric generating system is being developed to produce more than 35 kilowatts electric and to operate unattended for at least 10 000 hours in space after automatic startup. It will also have shutdown and restart capabilities.

The startup of SNAP-8 has three phases: (1) reactor startup during which the primary loop is brought to design temperature, (2) power-conversion system startup during which the mercury flow is brought to the self-sustaining level (minimum level for which turbine power is sufficient to maintain system operation, about 53.5 percent of design), and (3) a phase during which mercury flow is increased from the self-sustaining to the rated level. This report is concerned with condenser pressure control during the second phase of SNAP-8 startup. At the beginning of the second phase, the mercury inventory is injected into the evacuated second loop with a programmed ramp in flow rate as a function of time, this ramp brings the turboalternator to rated speed. When the injection process is completed, the mercury pump recirculates the liquid mercury from the condenser. Upon reaching the self-sustaining power level, the mercury flow rate is held constant until transients have settled out; it is then increased in a gradual manner to the full-power value.

During power conversion system startup, the condenser inlet pressure increases from zero to the design value. During the startup transient, conditions can exist which cause the pressure to rise much higher than the design value. These high pressures will occur if the cooling capacity of the NaK flowing through the condenser is too low relative to the heat input from the mercury loop. Since the condenser inlet pressure is also the turbine back pressure, high pressures must be avoided so as not to lower the turbine output power, especially when the turbine is accelerating. It is equally important to avoid low pressures throughout startup in order to maintain adequate net positive suction head (NPSH) for the mercury pump. Too low a pressure will reduce NPSH below the level required to prevent pump cavitation. Therefore, some form of pressure control is required to avoid the operating problems associated with the extremes of condenser pressure.

This report presents results of an experimental investigation of a deadband method of controlling the mercury condensing pressure during startup. With this method the pressure is controlled by varying the condenser coolant flow rate whenever the pressure goes outside a predetermined deadband. The test results of another method of control are detailed in reference 2. The tests were part of a series conducted in the W-1 test facility at Lewis (ref. 2). The rig was a test version of the SNAP-8 system containing all major components except the nuclear reactor and the radiator. The nuclear reactor was simulated by an analog-computer-controlled electric heater (ref. 3). The radiator was simulated by an analog-computer-controlled air blast heat exchanger which used the feedback circuit of reference 4. For the deadband tests closed-loop operation of the flow valve in the heat rejection loop was used to allow ramp changes in coolant flow to be made regardless of the loop's operating point.

The capability of the deadband pressure control was tested for various control parameters and outside disturbances. The effects of the following control parameters were studied: (1) pressure deadband width, (2) coolant-flow ramp rate, and (3) initial condenser coolant flow level. The effects of the following disturbances on the condenser were investigated: (1) condenser inventory (final value), (2) mercury-flow ramp duration, (3) initial condenser coolant inlet temperature, (4) initial condenser inventory, and (5) operating pressure level.

In the present report, only startups to the self-sustaining level of mercury flow are considered. The transients which occur during this portion of the startup are the most severe of the system startup and therefore provide the most crucial test of the deadband control.

APPARATUS AND INSTRUMENTATION

Test System

The test system was designed to simulate the basic SNAP-8 system. Essentially all of the major SNAP-8 components except for a nuclear reactor and a radiator were used. A schematic diagram of the basic test system with details relevant to the condenser deadband pressure control is given in figure 1. The analog-computer-controlled reactor simulator in the primary loop serves as the thermal energy source for the test system. A centrifugal pump circulates NaK to transfer this thermal energy to the boiler. During startup, operation of the primary loop occurs before operation of the mercury power generation loop. An auxiliary start heat exchanger is therefore used to transfer the thermal energy to the heat rejection loop during this interval.

In the power generation loop, liquid mercury is supplied to the boiler after passing through various valves (used for startup purposes) from a centrifugal pump. The liquid mercury is vaporized in the boiler and expanded through the turbine to drive an electrical alternator for useful power output. From the turbine the mercury vapor passed downward into the vertically mounted condenser where it was condensed and subcooled before again entering the centrifugal pump.

Prior to startup the mercury loop is evacuated. A supply of liquid mercury is contained in the standpipe and isolated from the system by valve V-217. A pressurized gas supply regulated by a manual loader in the control room is used to manipulate the mercury pump suction pressure during the injection of mercury into the loop. Valve V-210 at the condenser outlet serves to isolate the condenser during injection until condenser pressure builds up sufficiently for the pump.

The thermal energy leaving the mercury stream in the condenser was absorbed by the NaK flowing in the heat rejection loop. This thermal energy was in turn passed on to a radiator simulator as waste heat. The cooled NaK then entered a centrifugal pump, passed through the flow control valve V-314, through a magnetic flowmeter used for control and data purposes, and then into the condenser.

Condenser

The SNAP-8 condenser is a counterflow heat exchanger. It is a once-through unit. The unit was vertically mounted in the test facility. Externally it incorporated a tapered outer shell, which was larger at the top. Internally it contained a header from which the mercury vapor passes downward into 73 uniformly tapered tubes. The tapered tubes have their largest diameter at the mercury vapor end to allow high velocity in the condensing region. The ends of the tapered tubes were fitted with straight sections of tubing before joining the outlet header. Condenser operation was such that these sections were normally in the subcooled region. The tubes were installed with their centerlines angled to provide a constant NaK flow area in order to effect a constant NaK velocity along the critical-heat-transfer region of the condenser. The NaK entered the outer shell through a toroidal chamber, was circulated through the shell, and, after absorbing thermal energy from the condensing mercury vapor, was routed through the outlet toroidal chamber. Mechanical details of the condenser are described in reference 5.

Instrumentation

The instrumentation required to evaluate the operation of the condenser inlet deadband pressure control consisted of condenser mercury inlet and outlet static pressure transducers, the heat rejection loop NaK flowmeter at the inlet to the condenser, the load cell to indicate the weight change of the mercury in the standpipe, and the circuitry to indicate valve position. The pressure transducers were slack-diaphragm capillarytube units having an accuracy of 1 percent and operable to high temperatures. The heat rejection loop NaK flowmeter was a magnetic force type utilizing permanent magnets and giving a millivolt output signal proportional to flow rate. The standpipe weight was obtained by weighing the specially supported standpipe with strain-gage-type load cells. The instrumentation for the entire SNAP-8 simulator facility is detailed in reference 6.

The data acquisition system was a computerized digital system that scanned some 400 instrumentation channels every 11.4 seconds. The startup data figures in this report are traces of computer-plotted data that were recorded by this digital system.

DESCRIPTION OF DEADBAND PRESSURE CONTROL

A simplified block diagram representation of the deadband pressure control is shown in figure 2. The primary elements in the control loop are the deadband logic, the flow control, and the condenser. The function of the pressure control is to correct the condenser inlet pressure whenever it goes outside the deadband limits. This corrective action is taken by increasing the coolant flow when the pressure is above the upper limit and decreasing the flow when the pressure is below the lower limit. Control action begins when the pressure exceeds the upper deadband limit for the first time.

It was desired to change coolant flow at a constant rate on command with an existing valve. The valve did not have the appropriate area characteristic to accomplish this mode of operation with open-loop flow control. It was therefore necessary to design a closed-loop flow controller to get constant flow-ramp rates. The details of this flow control design and operation are discussed in the next section.

Flow Control

The flow control consisted of the following items:

(1) Modified valve actuator system for V-314

(2) Closed-loop feedback control on flow

(3) Electronic ramp generator

(4) Ramp control box

Modified valve actuator system. - Prior to the present series of tests valve V-314 located at the NaK inlet side of the condenser (fig. 1) had been remotely controlled using a manual loader (air pressure regulator) which was connected by means of a pneumatic line passing into the test cell to a pneumatic pilot valve mounted on the valve actuator for valve V-314. The valve actuator was a pneumatically operated piston attached to the valve stem. A helical spring had been built within the actuator under its piston so that on loss of air pressure the valve would fail safe open. During actual test runs the valve was operated off a regulated nitrogen gas supply so that it would not vent air into the nitrogen cover gas within the test cell. The pneumatic pilot valve to pneumatic cylinder operator incorporated local pneumatic feedback for accurate valve positioning from a pneumatic pressure signal. The overall pneumatic characteristic of pilot valve, operator, and NaK flow valve was such that full pressure input was required to drive the NaK valve closed.

The operation of this valve was modified to result in the system shown in figure 3. Incorporation of an automatic-manual solenoid allowed for either mode of operation. Utilization of an electropneumatic converter allowed electronic manipulation of the valve. The addition of an emergency vent solenoid allowed for rapid venting of the pneumatic line in order to drive the valve open should the need arise. Incorporation of a differential pressure pickup directly across the pneumatic line served to indicate any pneumatic signal unbalance which could be adjusted to zero by operation of the manual loader or flow controller prior to switching the mode of operation. These components were all positioned just outside the test cell close to the location of the valve within the test cell in order to keep the pneumatic line from the electropneumatic converter to pilot valve relatively short.

The differential pressure pickup was powered from a signal conditioning unit. The electrical output from the differential pressure pickup was amplified by a differential amplifier and displayed by means of a zero-center meter located in the control room.

Closed-loop feedback control on flow. - A block diagram representation of the closed-loop feedback control on flow is included as part of figure 4.

The closed-loop feedback control worked as follows: The millivolt output from the heat rejection loop NaK permanent magnet flowmeter was paralleled off from the instrumentation monitoring system by means of a precision high gain differential amplifier which boosted the flow signal up to the level of several volts. This constituted the feedback of the control. This signal was then set to a controller in the forward circuit of the control. The controller was constructed using analog-computer-type operational amplifiers. The flow feedback signal, the set point, and the ramp injection signal were summed in proportional and integral amplifiers each having independent gain adjustment. The outputs of these amplifiers were summed by a power booster amplifier which was capable of driving the electropneumatic converter. The controller was tuned for non-oscillation when operating the system at its point of highest sensitivity.

Electronic ramp generator. - The electronic ramp generator was constructed using a chopper stabilized operational amplifier which was adjusted to have a very small drift characteristic for long-term operation. A high quality condenser was used in its feedback path to produce an integrator. A switch in series with a resistor was also placed across the feedback path to allow discharging of the capacitor for balancing or resetting.

Ramp rate controller. - The ramp rate controller was powered from the precision regulated power supply used to power the operational amplifiers. The power supply had symmetrical plus and minus capability. The plus and minus voltages from this supply were tapped down to be appropriate for a precision potentiometer calibrated in terms of flow ramp rate. Two switches were incorporated in the ramp rate controller. Turning on one switch would cause a calibrated dc signal to be sent to the ramp generator which in turn sent a calibrated ramp signal to the controller calling for a specified ramp in flow. Turning off the switch would remove the signal from the ramp generator causing it to hold at its current value. The other switch functioned similarly to cause a ramp decrease.

The ramp controller was cabled to be directly at the site of the condenser inlet pressure monitoring station where the pressure was displayed by means of a wide angle taut band meter movement mounted on the control panel (fig. 4).

PROCEDURE

Test Procedure for Startup

The system conditions are brought through the following sequence during the power conversion system startup. This is phase 2 of SNAP-8 startup.

Initial conditions:

(1) Primary NaK loop in operation

(2) Mercury loop filled from V-210 to V-260 but nonflowing (fig. 1)

(3) Mercury standpipe filled

(4) Mercury pump running deadheaded

(5) Heat rejection loop pump operating on auxiliary power at 400 hertz

NaK-flow controller:

(1) The NaK flow controller is dialed to the flow desired with the pump operating at rated speed.

(2) The loader on V-314 was adjusted to bring the unbalance in pneumatic control line pressure to zero as indicated on the zero-center meter.

(3) The integral action of the flow controller was turned off.

(4) The V-314 mode of operation was switched to manual.

Mercury loop startup:

(1) The auxiliary source powering the pumps was reduced from 400 hertz to the pump transfer frequency thus reducing the heat rejection loop NaK flow from the design level because V-314 position was held fixed.

(2) The auxiliary loop flow was shut off by closing V-117.

(3) The mercury injection valve V-217 is opened in preparation for mercury injection.

(4) Thirty seconds before the beginning of the mercury flow ramp the valve at the boiler inlet V-260 was opened and the mercury flow control valve V-230 was opened slightly to provide a flow feedback signal for the valve controller. At the end of this 30-second period the mercury flow ramp to the self-sustaining level began.

(5) As the turbine frequency passed through the pump transfer frequency the pumps were transferred from auxiliary power to alternator power. This caused an increase in flow of the heat rejection loop as the pump accelerated toward the 400-hertz operating frequency.

(6) Near the end of the mercury flow ramp the condenser isolation valve V-210 was opened. The injection valve V-217 was closed when the desired amount of mercury had been injected into the loop.

Condenser pressure control:

(1) As the heat rejection loop pump reached 400-hertz operation, the mode of V-314 was switched to automatic and the integral action of the controller turned on.

(2) When the buildup in condenser inlet pressure exceeded the upper deadband limit as indicated on an accurate wide angle meter, an upward ramp signal calling for increased flow was sent to the flow controller.

(3) As the effect of the increased NaK flow caused the condenser inlet pressure to pass downward into the deadband, the signal calling for increased flow was switched off. This resulted in the flow of the heat rejection loop being maintained steady at its current value.

(4) Should the condenser inlet pressure continue to pass downward and go below the lower deadband limit, then a downward ramp signal calling for decreased flow was sent to the flow controller (upward or downward ramps were always at the same rate).

(5) As the effect of the decreased NaK flow caused the condenser inlet pressure to rise above the lower deadband limit, the signal calling for increased flow was switched off resulting in the heat rejection loop flow being maintained steady at its current value.

(6) This procedure of ramp initiation at the deadband limits was continued in order to maintain condenser inlet pressure at acceptable levels during system operation at the self-sustaining level.

Data Reduction

Condenser inventory was determined by use of the solid curve in figure 5(a) for operation at the self-sustaining level. The first point on the curve was determined by plotting condenser Δp at what was estimated to be zero condenser inventory. Condenser inventory was assumed to be zero when the pressure at the condenser outlet was equal to the saturation pressure at the outlet. Condenser inventory as defined here includes that in the the exit plenum. Plenum capacity is approximately 7 pounds (3 kg). The rest of the curve was generated by recording the change in standpipe weight, when additional mercury was added to the system and the corresponding change in condenser Δp. The increase in condenser inventory was assumed equal in magnitude to the decrease in standpipe weight (i.e., boiler inventory was assumed constant for the duration of the mapping).

The dashed curve shows the condenser inventory as a function of condenser Δp due to liquid head alone. The solid curve was intended primarily to provide an estimate of condenser inventory for the runs discussed in this report. However, the two curves of figure 5(a) also provide an estimate of the pressure rise or drop across the condenser that would exist in a zero-g environment. A plot of this zero-g Δp as a function of condenser inventory will be shown and discussed later in the report.

For accuracy in estimating the inventory and pressure drop, the inlet pressure should have remained constant at the reference value of 14 psi (9.6 N/cm^2) throughout the mapping. However, the inlet pressure varied from approximately the reference pressure at high condenser inventories to as low as 5.0 psi (3.4 N/cm^2) at low condenser inventories. Consequently, the solid curve should be least accurate for predicting inventory and pressure drop at the low inventory end for the runs discussed in the report. However, another method of estimating condenser inventory, which involved using the total amount of mercury injected in the system for each run (as calculated from the change in mercury standpipe weight) minus an assumed boiler inventory, gave reasonable agreement with the predictions of figure 5(a) over the whole range of inventories.

In figure 5(b) a similar curve is shown for the rated level of operation.

RESULTS AND DISCUSSION

Effect of Deadband Width

It is seen in the block diagram of figure 2 that the deadband logic contributes a nonlinear factor to the overall gain of the control; it is expected, therefore, that variations in the deadband width affect the stability of the control. For a typical startup the condenser inlet pressure rises to the upper deadband limit, oscillates a few times, and then settles out within the deadband limits. A computer study of the deadband pressure control for SNAP-8 startup (ref. 7) determined that decreasing the width of the deadband increases the frequency and duration of the oscillations. However, the magnitude decreases in accordance with the decrease in deadband width with no apparent increase in overshoot. For a deadband width of 1.5 psi (1.0 N/cm^2), which is the smallest width tested during the ramp to the self-sustaining level, the oscillations that existed were approximately equal to the deadband width. Thus it appears that the primary factor in determining the minimum allowable deadband width may be the desire to limit the frequent reversal of flow valve direction rather than the margin of stability. The 1.5 psi (1.0 N/cm^2) deadband width run is compared in the following discussion with a run of slightly larger deadband width.

The data obtained did not allow a direct demonstration of the effect of deadband width on controllability of condensing pressure since the effect of deadband width also included the effects of changes in other parameters. The best opportunity from the data obtained for showing the effect of deadband width is by comparison of two runs with different deadband widths but also with different pressure levels and condenser inventories. The effects of operating pressure level and condenser inventory were determined separately, and, for the runs considered, it is possible to separate out these effects and see the qualitative effect of deadband width. Unfortunately the difference in deadband width is too small to show a marked difference in response.

Figure 6(a) shows a plot of condenser inlet pressure response for a run with a deadband width of 1.5 psi (1.0 N/cm^2). This run should be compared with the data which resulted from the use of a 2.0 psi (1.4 N/cm^2) deadband width (see fig. 6(b)). It is seen that the response for the run with the smaller deadband width is more oscillatory. The run with the smaller deadband width is also at a lower operating pressure level. It will be shown later, however, that differences in pressure level of the order of 2.0 psi (1.4 N/cm^2) at a 10 psi (6.9 N/cm^2) pressure level do not significantly affect the control response. Condenser inventory is also lower for the run of figure 6(a). However, since a decrease in condenser inventory tends to result (it will later be shown) in less oscillatory response, the smaller deadband width of figure 6(a) should be responsible for its more oscillatory nature.

The conclusion derived from the runs shown is that decreasing the deadband widths below 2.0 psi (1.4 N/cm^2) results in such frequent reversal of flow control valve direction that it should probably be avoided.

In figure 6(b) it should be noted that after a few oscillations within the deadband the condenser inlet pressure settles out and "rides" the upper deadband. This riding of the upper deadband limit is a result of the gradual increase in condenser NaK inlet temperature during this period. (After about 330 seconds the two runs cannot be compared for effect of deadband width because of the difference in temperature between the runs.) The rise in condenser NaK inlet temperature is reflected in the gradual rise of condenser mercury outlet temperature which is also shown plotted in figure 6(a). The rise in coolant inlet temperature requires an increasing flow of coolant to maintain the same cooling capacity and keep the pressure at the same level; thus, the slowly increasing NaK inlet temperature explains the riding of the upper deadband. From data not shown (for the run of fig. 6(b)) it was found that the NaK flow rate rose from its initial value (after bootstrapping) of 6500 pounds per hour (2950 kg/hr) to a peak value of 18 300 pounds per hour (8300 kg/hr) shortly after condenser coolant inlet temperature reached its peak value; the NaK flow rate then settled out at the plateau level of 13 700 pounds per hour (6210 kg/hr) after the coolant inlet temperature reached its final value.

Effect of NaK Flow Ramp Rate

NaK flow ramp rate is also a factor in the overall gain of the control and therefore should have a major effect in determining the degree of stability of the control. In the block diagram of figure 2 the NaK flow ramp rate is represented by the gain K in the approximate transfer function K/S of the flow controller. Increasing the NaK flow ramp rate tends to increase the frequency of the inlet pressure oscillation during the startup transient; increasing the ramp rate also tends to decrease the initial overshoot of the upper deadband limit. It should be expected that excessively large ramp rates might result in frequent control valve cycling. Ramp rates that ranged from 15 to 600 pounds per hour-second (6.8 to 272 kg/hr-sec) were tested; four runs with ramp rates of 600, 200, 100, and 15 pounds per hour-second (272, 90.8, 45.4, and 6.8 kg/hr-sec) are discussed in the remaining part of this section.

The effect of the control parameter NaK flow ramp rate can be seen by comparing figures 7(a) and (b). Figure 7(b) shows a condenser inlet pressure trace for a NaK flow ramp rate of 200 pounds per hour-second (90.8 kg/hr-sec). When this parameter is increased to 600 pounds per hour-second (272 kg/hr-sec) the pressure response becomes much more oscillatory as shown in figure 7(a).

The initial overshoot of the upper deadband is greater for the lower than for the higher ramp rate. A larger overshoot for the lower ramp rate should be expected since a higher ramp rate means faster control response. The irregular nature of the overshoot in figure 7(a) is probably due to one or more of the following reasons:

(1) The system is by nature nonlinear.

(2) The data were taken at 11-second intervals; therefore, the pressure peaks were probably not recorded in some cases.

(3) The control was actuated and deactuated manually according to visual reading of a meter; therefore, any error involved in switching is inherently irregular in nature. In the computer study of reference 7 the overshoot during oscillations was also irregular; thus, one would suspect the nonlinear nature of the system was at least partially responsible for the irregularity.

In figure 7(c) a run is shown for which a ramp rate of 100 pounds per hour-second (45.4 kg/hr-sec) was used. Since most of the other parameter values are somewhat different than the corresponding values for the runs of figures 7(a) and (b), a direct quantitative comparison cannot be made. Thus, it is not clear whether a 100-pound per hour-second (45.4-kg/hr-sec) ramp rate would allow a significantly larger overshoot than a 200-pound per hour-second (90.8-kg/hr-sec) ramp rate for the same set of parameter values. If overshoot is not a problem, then a ramp rate of 100 pounds per hour-second (45.4 kg/hr-sec) would appear to be satisfactory. It is seen that the pressure plot in figure 7(c) settles out and rides the upper deadband limit in contrast to the pressure plot of figure 7(b). This difference in response occurs because NaK inlet temperature rises faster for the run of figure 7(c) than for the run of figure 7(b). This effect can be seen by reference to the plots of condenser mercury outlet temperature in figures 7(b) and (c). Mercury outlet temperature is very close in value to NaK inlet temperature after 3 minutes. The relatively rapid rise in NaK inlet temperature for the run of figure 7(c) is probably due to both its lower ramp rate and lower initial NaK flow.

In figure 7(d) a run is shown for which a ramp rate of 15 pounds per hour-second (6.8 kg/hr-sec) was used. Here again there are parameter differences which make it difficult to evaluate this run relative to the others that have been discussed. The initial NaK flow rate is especially high at 7500 pounds per hour (3400 kg/hr) as compared to values in the range from 6000 to 6500 pounds per hour (2720 to 2950 kg/hr) for the previous three runs. The response shown in figure 7(d) is satisfactory as far as overshoot is concerned. However, the condenser inlet pressure at the end of injection is marginal. Therefore, for a nominal startup decreasing the coolant flow ramp rate requires increasing the initial NaK flow to control the overshoot. However, if the initial NaK flow is too large there will not be adequate pressure at the end of injection.

To avoid overworking the control it should be operated with as small a ramp rate as is possible without violating other operating restrictions. It will probably be necessary to use ramp rates larger than 100 pounds per hour-second (45.4 kg/hr-sec). Optimization of the control parameters might result in a NaK flow ramp in the range from 100 to 200 pounds per hour-second (45.4 to 90.8 kg/hr-sec) for a 50-pound (23-kg) final condenser inventory, a 110° F (317 K) condenser NaK inlet temperature, and a 100-second mercury ramp. Changes in the disturbances which increased overshoot could require even larger ramp rates. A ramp rate of 600 pounds per hour-second (272 kg/hr-sec) with a 3.0 psi (2.1 N/cm^2) deadband produced excessive oscillations and would appear to be an upper limit on ramp rate.

Effect of Initial Coolant (NaK) Flow Rate

The initial NaK flow rate through the condenser is a parameter which can be used to adjust the value of the condenser inlet pressure at the end of injection; the value of this pressure at the end of injection should be somewhat greater than 1 psi (0.7 N/cm^2) to ensure adequate NPSH at the pump inlet. In the block diagram of figure 2 the initial NaK flow rate is shown as an initial condition of the flow controller. The ramp input signal to the flow controller is zero until the pressure reaches the upper deadband limit for the first time. The condenser disturbances of mercury ramp rate, condenser inventory, and NaK inlet temperature also affect the value of the pressure at the end of injection, but the values of these disturbances will be determined primarily by other considerations. Decreasing the initial NaK flow rate tends to increase the pressure at the end of injection but also tends to increase the initial overshoot of the upper deadband limit. Therefore, the upper limit on the initial NaK flow is a function of the pressure at the end of injection while the lower limit is a function of initial overshoot of the upper deadband limit. As discussed in the previous section, NaK flow ramp rate also affects the initial overshoot of the upper deadband limit.

For the runs of figures 7(a), (b), and (c) (which had NaK flow ramp rates of 600, 200, and 100 lb/hr-sec (272, 90.8, and 45.4 kg/hr-sec), respectively), pressure at the end of injection was satisfactory with initial NaK flows (at 400 Hz) in the 6000 to 6500 pounds per hour (2720 to 2950 kg/hr) range. Pressures at the end of injection for the three runs were between 5.0 and 9.5 psi (3.4 and 6.5 N/cm^2) for figure 7(a), between 5.5 and 9.5 psi (3.8 and 6.6 N/cm^2) for figure 7(b), and between 2.0 and 3.0 psi (1.4 and 2.1 N/cm^2) for figure 7(c); the higher pressure levels of figures 7(a) and (b) may have been due to the fact that initial condenser NaK inlet temperature was 23° F (13 K) higher for these runs than for the run of figure 7(c). Initial overshoot was satisfactory for all three runs. The mercury plateau flow levels for figures 7(a) and (b) were 300 pounds per hour (136 kg/hr) higher than the design flow level of 6600 pounds per hour (3000 kg/hr); decreasing the plateau flow levels to the design levels for the two runs would tend to reduce the pressure at the end of injection. The plateau flow level of figure 7(c) was 200 pounds per hour (90.8 kg/hr) above the design level; reduction to the design level for this run might require a reduction in the initial NaK flow rate below 6000 pounds per hour (2720 kg/hr) to maintain adequate pressure at the end of injection.

For the run of figure 7(d) (15 lb/hr-sec (6.8 kg/hr-sec) flow ramp rate), the initial NaK flow rate was 7500 pounds per hour (3400 kg/hr). The pressure at the end of injection was 2.0 psi (1.4 N/cm^2). This value seems rather high for such a high level of initial NaK flow, but it is probably due to the relatively high level of condenser inventory, 68 pounds (31 kg) as compared with the other runs of figure 7.

Several additional runs are discussed to demonstrate the effect of initial NaK flow rate. Figures 8(a) and (b) can be compared to show some of the effects of initial NaK flow rate. The initial NaK flow is larger for the run of figure 8(a) (6200 lb/hr (2820 kg/hr) at 400 Hz) than for the run of figure 8(b) (5500 lb/hr (2500 kg/hr) at 400 Hz); all other parameters are approximately the same. The initial rate of rise of pressure is higher for the run with the lower initial NaK flow rate; there is consequently more initial overshoot of the upper deadband limit for the lower initial NaK flow rate. For the high flow rate of figure 8(a) pressure is at an acceptable value of 2.0 psi (1.4 N/cm^2) at the end of injection. For the run of figure 8(b) the pressure at the end of injection was 2.3 psi (1.6 N/cm^2) or slightly higher than for the run of figure 8(a).

Thus, for the set of parameter values given, pressures at the end of injection are at acceptable but marginal levels for initial NaK flow rates of 5500 and 6200 pounds per hour (2500 and 2820 kg/hr). The overshoot to 17 psi (12 N/cm^2) is too large for 5500 pound per hour (2500 kg/hr) initial NaK flow and 100 pound per hour-second (45.4 kg/hr-sec) NaK flow ramp rate (fig. 8(b)). In order to use an initial NaK flow rate of 5500 pounds per hour (2500 kg/hr) with the other parameter values it would be necessary to use a larger NaK flow ramp rate (150 or 200 lb/hr-sec (68.1 or 90.8 kg/hr-sec)) to control the overshoot. It should be noted that the mercury plateau flow for these two runs is 200 pounds per hour (90.8 kg/hr) higher than the design plateau flow of 6600 pounds per hour (3000 kg/hr). Reduction of the plateau flow to 6600 pounds per hour (3000 kg/hr) for the runs discussed would tend to reduce the pressure at the end of injection and therefore might require some reduction in initial NaK flow rate to maintain the pressure at the same levels.

Optimization of the control parameters would probably result in an initial NaK flow rate in the range from 5000 to 6500 pounds per hour (2270 to 2950 kg/hr) (at 400 Hz) for a condenser inventory of about 50 pounds (23 kg) and a condenser NaK inlet temperature of 110° F (317 K). It should be noted that increasing either condenser inventory or NaK inlet temperature tends to increase the pressure at the end of injection. Thus increasing either of the previous values of the condenser disturbances would tend to increase the optimized value of initial NaK flow rate.

Effect of Condenser Inventory on Condenser Vapor Pressure Drop

It was learned as a result of the test program that significant amounts of pressure drop can exist in the condenser for low inventory operation. The pressure drop caused no problems in the test loop because gravity provided sufficient mercury pump NPSH. It appears, however, that to ensure adequate mercury pump NPSH in a zero-g environment requires that some low limit be imposed on condenser inventory.

From the curves of figure 5 and inlet pressure characteristics (for the same set of data) it was possible to obtain plots of zero-g outlet pressure as a function of condenser inventory. Inlet and zero-g outlet pressure characteristics are plotted in figure 9 for the self-sustaining and rated operating levels. The curves of figure 9(a) indicate that some pressure drop (in zero-g) exists for the range of inventories from 0 to 35 pounds

(0 to 16 kg). The curve of figure 9(b) is for approximately the rated flow level; pressure drop is seen to exist for the range of inventories from 0 to 16 pounds (0 to 7.3 kg).

It is also seen in figures 9(a) and (b) that zero-g pressure rises as large as 3.0 and 1.7 psi (2.1 and 1.2 N/cm^2) are indicated for the self-sustaining and rated flow levels, respectively. The absolute and relative magnitudes of these pressure rises are such that they cannot be attributed to momentum pressure recovery alone. An estimate of the maximum possible pressure rise due to momentum recovery yielded 0.3 and 1.0 psi (0.2 and 0.69 N/cm^2) at the self-sustaining and rated flow levels, respectively. Errors in inventory and pressure measurements could be responsible for 2.0 and 3.0 psi (1.4 and 2.1 N/cm^2) errors in the condenser Δp. It should be noted that if the outlet pressure characteristics of figures 9(a) and (b) were shifted downward to yield more acceptable values of pressure rise, then pressure drop would be greater for the low inventory range.

It is clear that some low limit must be placed on condenser inventory. A 30-pound (14-kg) low limit might be adequate to avoid problems resulting from pressure drop. Making reliable estimates of condenser inventory, and therefore pressure drop, was difficult for the W-1 tests. To get more reliable information on condenser inventory and pressure drop will require a better method for determining condenser inventory than was used in these tests.

Effect of Condenser Inventory on Condenser Inlet Pressure Control

Consideration of vapor pressure drop in the condenser has resulted in recommendation that a low limit be established on the allowable range of condenser inventory; this recommendation was based on the requirement of maintaining adequate condenser outlet pressure at steady state when inlet pressure is satisfactory. Satisfactory control of condenser inlet pressure during startup requires that additional restrictions be placed on the allowable range of condenser inventory. Consideration is given in the following discussion to establishing restrictions on condenser inventory to ensure satisfactory control of condenser inlet pressure.

The effect of condenser inventory on condenser inlet pressure control can be seen by reference to the two traces of figure 10; all parameters except condenser inventory are the same. Condenser inventory is larger for figure 10(b) than for 10(a). It is seen that the rate of rise of the initial surge in pressure increases with increasing inventory. As a result, the initial overshoot tends to increase with increasing condenser inventory. Also, the pressure response is seen to be more oscillatory for the higher inventory.

The most critical factor in determining the low limit on condenser inventory (as far as inlet pressure control is concerned) is the condenser inlet pressure at the end of injection. It is seen from the two figures previously discussed, that the pressure at the end of injection increases with increasing condenser inventory. Condenser inlet pressure at the end of injection is plotted as a function of condenser inventory in figure 11 for three runs with 60-second ramps (two of these are the runs of fig. 10) and also for three runs with 100-second mercury ramps.

From figure 12 it is seen that the required net positive suction head at 6600 pounds per hour (3000 kg/hr) mercury flow is about 1 psi (0.7 N/cm^2). Therefore, the condensing pressure at the interface must be in excess of 1 psi (0.7 N/cm^2) to avoid cavitation at the pump inlet (for zero-g operation). From figure 11 it is seen that a 1 psi (0.7 N/cm^2) minimum establishes a lower limit on condenser inventory of about 18 pounds (8.2 kg) for the 60-second mercury ramp to 6900 pounds per hour (3130 kg/hr). For the 100-second ramp the pressure at the end of injection was satisfactory for the lowest inventory shown of 45 pounds (20 kg) and, by curve extrapolation, would appear to be satisfactory for inventories as small as 30 pounds (14 kg).

The following conclusions have resulted from the data previously discussed:

(1) The rate of rise of the initial surge in pressure and the pressure at the end of injection increase with increasing condenser inventory.

(2) With a 30-pound (14-kg) low limit on inventory (to avoid excessive pressure drop), pressure at the end of injection should be satisfactory for mercury ramps as long as 100 seconds with a 6000-pound per hour (2720-kg/hr) initial NaK flow.

The question of what upper limit must be set on condenser inventory cannot be definitely answered from the data obtained. The upper limit would probably be a function of the amount of initial overshoot of the upper deadband. For the runs of figures 6(a) and (b) with inventories of 86 and 102 pounds (39 and 46.4 kg), respectively, the initial overshoots were 5.0 and 6.0 psi (3.4 and 4.1 N/cm^2), respectively. The significant parameter differences for these runs as compared to the runs of figure 10 are NaK flow ramp rate and initial condenser NaK inlet temperature. The lower ramp rates of figure 6 would tend to increase the overshoot, but the lower initial condenser inlet temperatures would tend to decrease overshoot. A run with parameters comparable to those of figure 10 except for a final condenser inventory of 100 pounds (45.4 kg) would probably yield an initial overshoot of 5.0 or 6.0 psi (3.4 and 4.1 N/cm^2) or less. Thus, 100 pounds (45.4 kg) would appear to be an upper limit on condenser inventory for startup purposes.

Effect of Mercury Ramp Duration on Condenser Pressure Control

The runs discussed in this section show that the pressure control can perform adequately for all mercury ramps to the self-sustaining level of duration between 30 and

100 seconds in length. It may be possible to adequately control the pressure for ramps of duration as long as 140 seconds, but this is not clear from the data. It was concluded from other tests that a 100-second ramp was a good compromise between a ramp that was too short, which would prohibit use of open loop mercury flow control, and a ramp that was too long. Ramps that are too long result in turboalternator deceleration when the speed control is added to the alternator. A ramp rate of 140 seconds resulted in a slight amount of deceleration of the turboalternator when the speed control was activated. When a ramp rate of 145 seconds was used the turboalternator speed decreased sharply when the speed control was activated and the pump electrical loads were removed from the alternator to avoid possible stalling of the turbine.

Runs made with 30- and 60-second ramps are shown in figures 13(a) and (b), respectively. It is seen that the overshoot is greater and the pressure at the end of injection is higher for the faster ramp. However, inventory is also larger for the run of figure 13(a). Therefore, the greater overshoot and higher pressure at the end of injection is due partly to the larger inventory and partly to the faster ramp. The pressure at the end of injection was found to be 16.5 psi (11.4 N/cm^2) for figure 13(a) and 10.5 psi (7.2 N/cm^2) for figure 13(b).

Runs made with 100- and 140-second ramps are shown in figures 13(c) and (d), respectively; other parameters are approximately the same for the two runs. It is also true for these two runs that the pressure at the end of injection is higher for the faster ramp. However, for these two runs, the overshoot is smaller for the faster ramp. This may be due to the fact that the inventory is slightly larger, by 5.0 pounds (2.3 kg), for the slower ramp. The pressure at the end of injection is zero for the 140-second ramp and was found to be about 3 psi (2 N/cm^2) for the 100-second ramp. Therefore, the data indicate that severe pump cavitation would have resulted if the run of figure 13(d) had been conducted in zero-g.

Thus mercury ramp duration has a significant effect on pressure at the end of injection. In general, the pressure at the end of injection decreases with decreasing ramp rate. Pressure at the end of injection was not adequate for the 140-second run discussed; it is possible that this pressure could have been made adequate by decreasing the initial NaK flow and controlling any additional overshoot by increases in NaK ramp rate.

Figure 13(c) shows that for the nominal disturbances, 100 second mercury ramp rate, 70-pound (32-kg) final condenser inventory, and 120° F (322 K) initial condenser NaK inlet temperature an initial NaK flow rate of 6000 pounds per hour (2720 kg/hr) gave sufficient pressure at the end of injection. A NaK flow ramp rate of 150 pounds per hour-second (68.1 kg/hr-sec), together with the 6000 pound per hour (2720 kg/hr) initial flow rate, was sufficiently large to control the overshoot. Oscillations were satisfactory with this ramp rate and a 3.0 psi (2.1 N/cm^2) deadband. Figure 6(b) indicates that these control parameters were acceptable for inventories as large as 100 pounds (45.4 kg); a figure discussed later in the report (fig. 15(a)) indicates that these parameters are satisfactory for inventories as small as 45 pounds (20 kg) (with other disturbances approximately the same).

Effect of High Condenser NaK Inlet Temperature On Condenser Pressure Control

For most of the startups made the initial condenser NaK inlet temperature was in the 110° to 130° F (317 to 328 K) range. For one of the startups this initial temperature was 285° F (414 K). The relative effect of this unusually high temperature can be seen in figure 14. Figure 14(a) shows the run with the 285° F (414 K) initial temperature. For comparison, a run with a 130° F (328 K) initial condenser NaK inlet temperature is shown in figure 14(b). Other parameter values for the two runs are shown in the accompanying tables.

The run with the high inlet NaK temperature shows a much faster rise in condenser inlet pressure and consequently a much higher overshoot; the peak pressure is about 22 psi (15 N/cm^2) for the run of figure 14(a) and only 17 psi (12 N/cm^2) for the run of figure 14(b).

There are differences between the runs in two of the other parameters which should be mentioned:

(1) The condenser inventory was higher for the run of figure 14(b) than for the run of figure 14(a) (44 lb (20 kg) as compared to 36 lb (16 kg)). Since higher inventory tends to produce greater overshoot, the overshoot of figure 14(a) would have been even greater if the inventory had been 44 pounds (20 kg).

(2) The initial NaK flow rate was lower for the run of figure 14(a) than for that of figure 14(b) (6000 lb/hr (2720 kg/hr) as compared to 6500 lb/hr (2950 kg/hr)). Increasing the initial flow to 6500 pounds per hour (2950 kg/hr) for the run of figure 14(a) would tend to reduce the overshoot. Judging from the runs of figure 8, which show the effect of initial NaK flow rate, increasing NaK flow rate to 6500 pounds per hour (2950 kg/hr) for the run of figure 14(a) might reduce the overshoot by 1 or 2 psi (0.7 or 1 N/cm^2). Thus, the peak pressure would still be 20 or 21 psi (14 or 15 N/cm^2).

Pressure peaks as high as 21 psi (15 N/cm^2) should be avoided; pressures in excess of 21 psi (15 N/cm^2) might even stall the turbine. No perturbations in turbine frequency are observed in the trace of figure 14(a) as a result of the high peak in pressure. (Note that the turbine-alternator frequency trace is shown.) However, since there were no pumps on the alternator for this run, the entire load consisted of the parasitic load of the speed control. Therefore, when the peak in pressure reduced the applied torque on the turbine, the speed control (with its resistive load much larger than it would be with all pumps on the alternator) was able to reduce the load sufficiently to control speed. For the run of figure 14(c), however, all pumps were on the turbine and the resistive load of the speed control was correspondingly smaller. Therefore, when the pressure reached its peak of 21 psia (15 N/cm^2) the speed control was unable to control the speed because its resistive load was already reduced to zero. As seen from the trace of turbine frequency, the frequency dipped at the pressure peak. The low initial NaK flow and high plateau flow level are apparently responsible for the pressure spike of figure 14(c). Therefore, with an initial condenser NaK inlet temperature of 285° F (414 K), the initial NaK flow would have to be rather high to control the overshoot. For this reason it appears that an initial inlet temperature of 285° F (414 K) might preclude having both adequate pressure at the end of injection and sufficient margin above the peak overshoot.

Effect of Different Initial Inventories in Condenser

The SNAP-8 system is being designed for shutdown and restart capability in the zero-g environment. In such an environment the amount of inventory remaining in the system from shutdown to shutdown will probably not be consistent. Therefore the amount of initial inventory in the condenser from startup to startup will probably vary.

The runs of figure 15 are compared in an effort to determine the effect, if any, of the initial amount of condenser inventory on condenser inlet pressure control. The run of figure 15(b) is seen to have a more oscillatory response of condenser inlet pressure than the run of figure 15(a). The initial condenser inventory was 43 pounds (20 kg) for figure 15(b) and only 2 pounds (0.9 kg) for figure 15(a). There were some other differences which should be noted:

(1) The initial NaK flow rate was 500 pounds per hour (227 kg/hr) higher for figure 15(b) than for figure 15(a). However, the higher flow rate should tend to make the run of figure 15(b) less oscillatory.

(2) The condenser isolation valve (V-210) opened at least 11 seconds and possibly as long as 33 seconds after the end of injection for figure 15(b). For the run of figure 15(a) the condenser isolation valve opened within the same 11-second interval (data points were recorded at 11-sec intervals) that injection ended. If the isolation valve did open somewhat later for the run of figure 15(b), this would tend to make the condenser inventory at the end of injection even higher.

(3) Both mercury flow schedules were somewhat erratic. However, injection had ended for both runs by the time the pressure had reached the lower deadband limit. Therefore, differences in flow schedule were probably not responsible for the more oscillatory nature of figure 15(b).

The fact that injection ends later for the run of figure 15(b) than for 15(a) is contrary to what one would expect, since about 40 pounds (18 kg) less inventory is injected in the case of the run of figure 15(b). This was due to the irregular injection schedule of the figure 15(b) run. Toward the end of the injection period mercury was actually removed from the loop for a short period. Thus no conclusions can be drawn as to the effect of initial condenser inventory on the pressure at the end of injection.

From these runs it appears that increasing the initial condenser inventory tends to make the response of condenser inlet pressure more oscillatory. Although this conclusion seems reasonable, it is subject to doubt because of the irregular mercury flow ramp. For the runs shown, the effect was probably magnified somewhat by a delay in opening the condenser isolation valve.

Effect of Condenser Operating Pressure Level on Condenser Pressure Control

It might be expected, from the nonlinear nature of the mercury vapor saturation curve, that the behavior of the controlled condenser inlet pressure might be significantly dependent on operating pressure level. The runs of figure 16 are shown in an attempt to determine the effect of pressure level. All parameters for the two runs are approximately the same except for initial NaK flow rate and pressure level. The deadband width of figure 16(a) is 3.0 psi (2.1 N/cm^2) and lies between the limits of 10 and 13 psi (6.9 and 9.8 N/cm^2). The deadband width of figure 16(b) is also 3.0 psi (2.1 N/cm^2) and lies between the limits of 11.5 and 14.5 psi (7.9 and 10.0 N/cm^2).

There is no marked difference between the two runs that can be definitely attributed to the difference in operating pressure level. There is only a small difference in the pressure levels, 1.5 psi (1.0 N/cm^2), so this is not too surprising. The fact that the pressure begins riding the upper deadband earlier for the run of figure 16(b) is the result of a higher rate of increase in condenser NaK inlet temperature; this higher rate is probably due to the higher initial NaK flow rate of figure 16(b) (6500 lb/hr (2950 kg/hr) as compared to 6000 lb/hr (2720 kg/hr) for the run of figure 16(a)).

No definite conclusion can be drawn as to the effect of operating pressure level on condenser pressure control. However, a small change in pressure level, 1.5 psi (1.0 N/cm^2), did not significantly affect the control response.

CONCLUDING REMARKS

Control parameters were selected to try to produce the following characteristics in the pressure response: (1) enough pressure at the end of injection to ensure adequate mercury pump NPSH for zero-g operation, (2) small initial overshoot to avoid degradation in turbine power, and (3) minimum oscillations to minimize control valve operation.

Pressure at the end of injection is affected by the initial NaK-flow control parameter and by the disturbances - mercury-flow ramp rate, final condenser inventory, and initial NaK inlet temperature. Initial overshoot is affected by the control parameters of NaK-flow ramp rate and initial NaK flow as well as by the disturbances mentioned previously. The oscillations are affected primarily by NaK-flow ramp rate and deadband width.

For the disturbances of 100-second mercury ramp, 70-pound (32-kg) final condenser inventory, and 120° F (322 K) initial condenser NaK inlet temperature, an initial NaK flow rate of 6000 pounds per hour (2720 kg/hr) gave sufficient pressure at the end of injection. The NaK flow ramp rate of 150 pounds per hour-second (68.1 kg/hr-sec) was sufficiently large to control the overshoot and, with a 3.0 psi (2.1 N/cm^2) deadband (11 to 14 psi (7.6 to 9.7 N/cm^2)), the oscillations were also satisfactory. These control parameters were acceptable for inventories as large as 100 pounds (45.4 kg) and for inventories at least as small as 45 pounds (20 kg). These parameters might have been satisfactory for inventories as small as 30 pounds (14 kg) but there are no data to verify this. Inventories smaller than 30 pounds (14 kg) are unacceptable because of the necessity for avoiding excessive condenser pressure drop.

Mercury ramps as short as 30 seconds were used satisfactorily with inventories as large as 45 pounds (20 kg) and inlet temperatures as high as 130° F (328 K) when the initial flow and flow ramp rate were increased to 6500 pounds per hour (2950 kg/hr) and 200 pounds per hour-second (90.8 kg/hr-sec), respectively, to control the initial overshoot. When a 30-second mercury ramp was used with a very high initial NaK inlet temperature of 285° F (414 K) (and 35-lb (16-kg) inventory) with only a 6200 pound per hour (2820 kg/hr) NaK flow and a 200 pound per hour-second (90.8 kg/hr-sec) NaK ramp rate, a pressure overshoot resulted which was high enough to cause a momentary dip in turbine frequency. However, if the initial NaK flow and ramp rate had been increased even further, it might have been possible to control the overshoot even with this high initial inlet temperature. There is a limit to how high the ramp rate can be made, however. A ramp rate of 600 pounds per hour-second (272 kg/hr-sec) with a 3.0 psi (2.1 N/cm^2) deadband (11 to 14 psi (7.6 to 9.7 N/cm^2)) resulted in excessive oscillations. Decreasing the deadband width also tends to increase the oscillations. A deadband width of 1.5 psi (1.0 N/cm^2) when used with a NaK ramp rate as small as 150 pounds per hour-second (68.0 kg/hr-sec) resulted in oscillations that were considered excessive.

It is concluded that a deadband condenser pressure control is capable of satisfactory operation during startup over a reasonably wide range of disturbances.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 21, 1970,
120-27.

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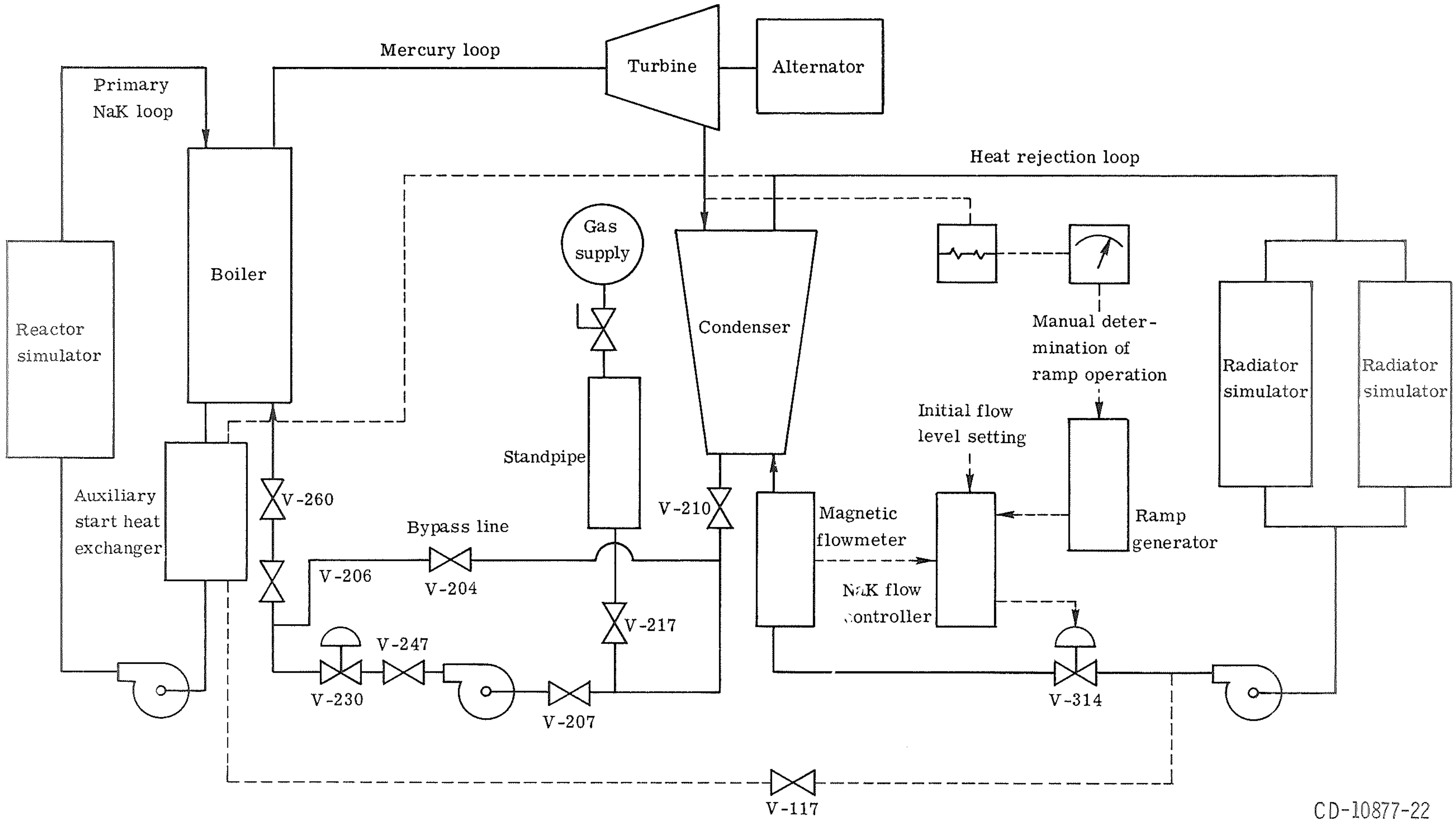


Figure 1. - Schematic of SNAP-8 test system.

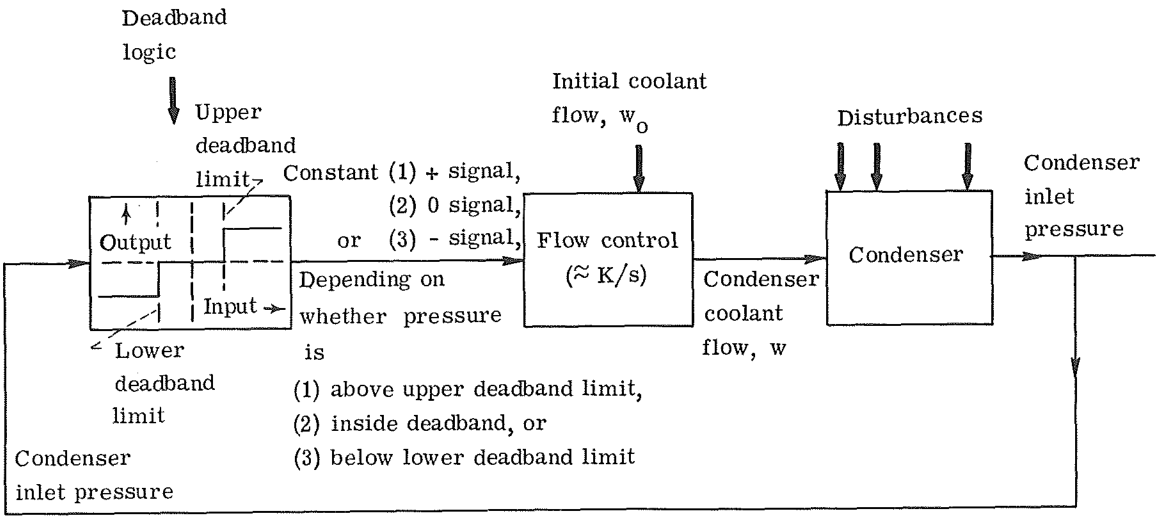


Figure 2. - Deadband pressure control.

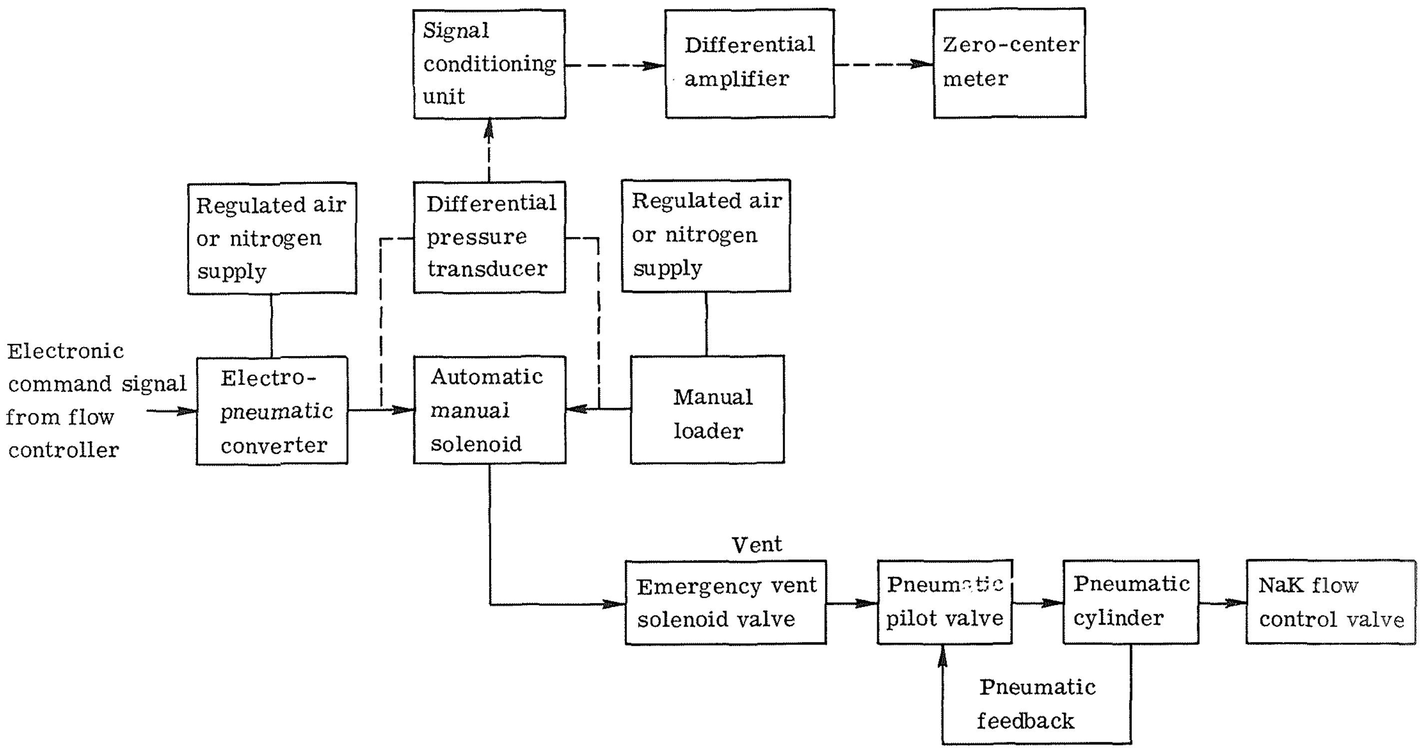


Figure 3. - Valve actuator system.

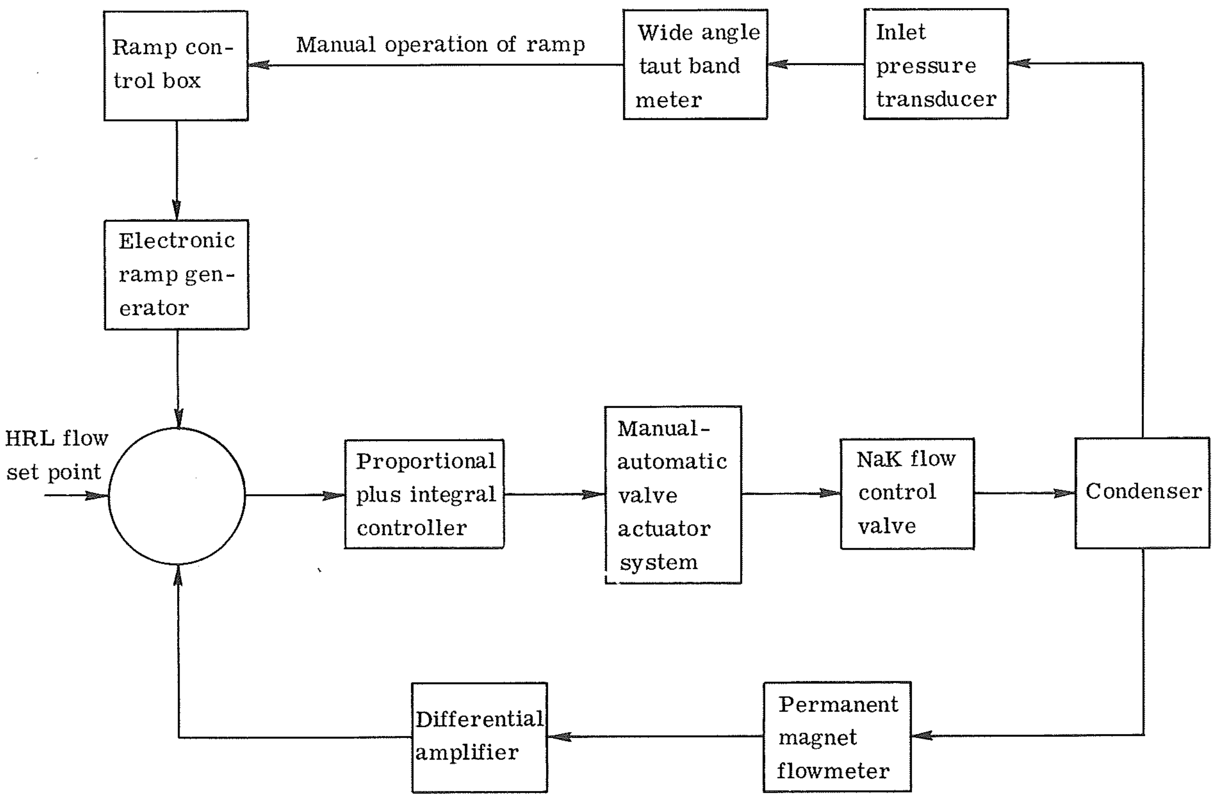
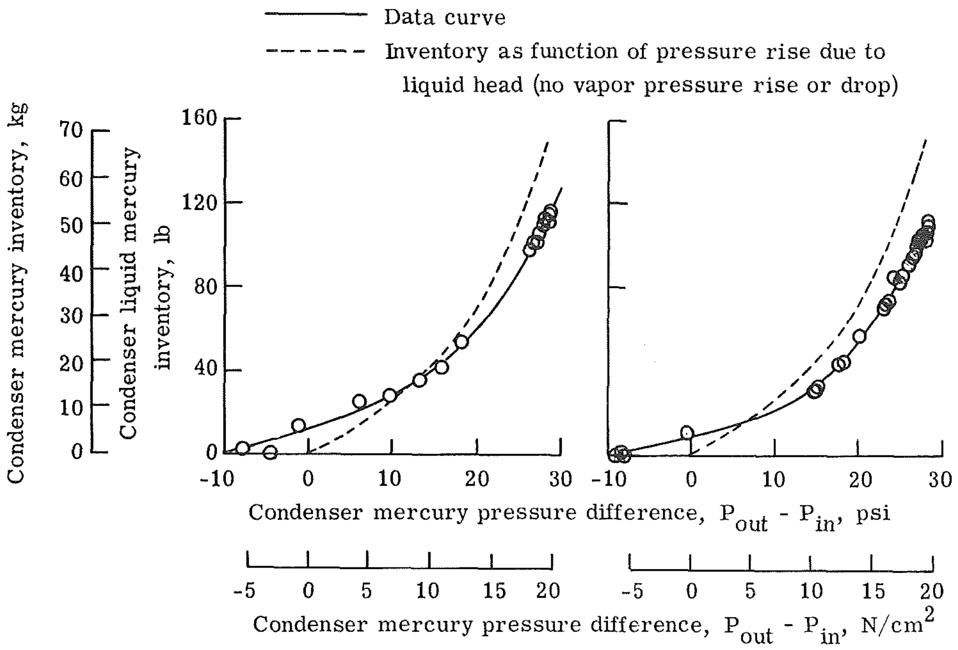


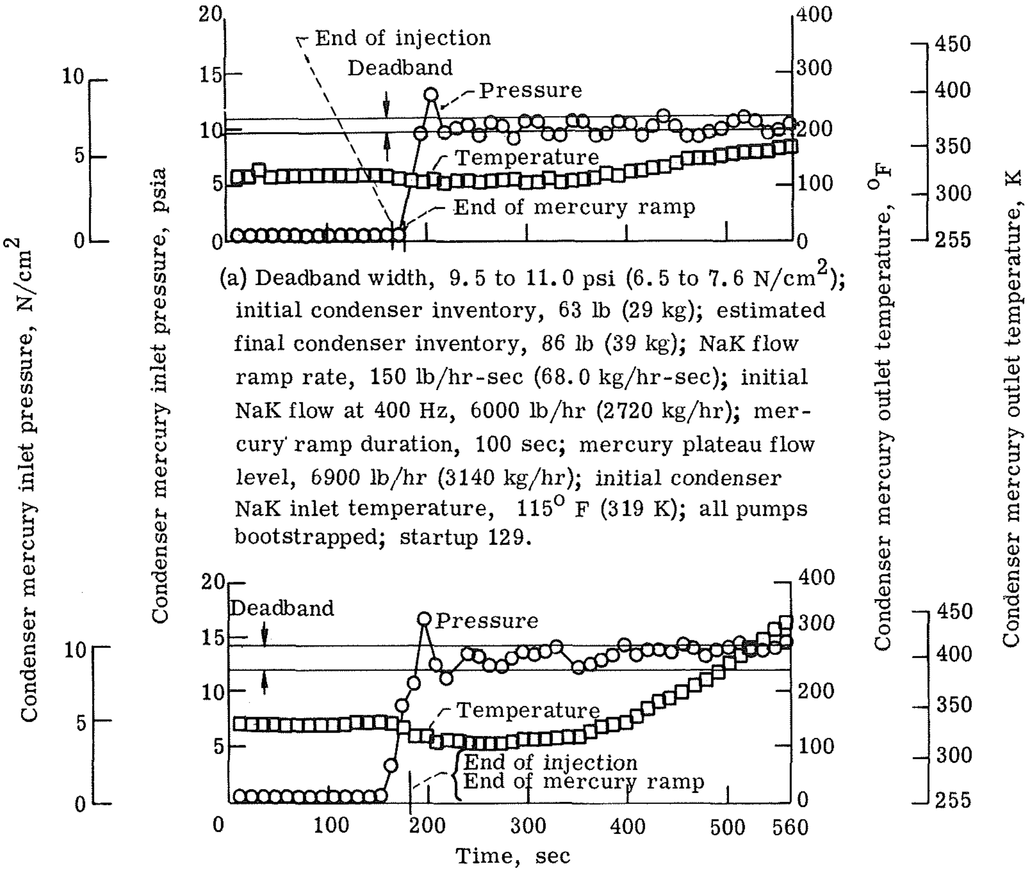
Figure 4. - Deadband control and flow control.



(a) Self-sustaining operation. Mercury flow, 6700 lb/hr (3040 kg/hr); NaK flow, 11 000 to 15 000 lb/hr (5000 to 6800 kg/hr); NaK inlet temperature, 280° to 317° F (411 to 431 K); inlet pressure ranged from 5.0 psi (3.4 N/cm^2) at low inventories to 16 psi (11.0 N/cm^2) at high inventories.

(b) Rated flow operation. Mercury flow, 12 300 lb/hr (5580 kg/hr); NaK flow, 29 500 to 41 500 lb/hr (13 400 to 18 800 kg/hr); NaK inlet temperature, 410° to 480° F (483 to 522 K); inlet pressure ranged from 10.5 psi (7.24 N/cm^2) for low inventories to 27.5 psi (18.9 N/cm^2) for high inventories.

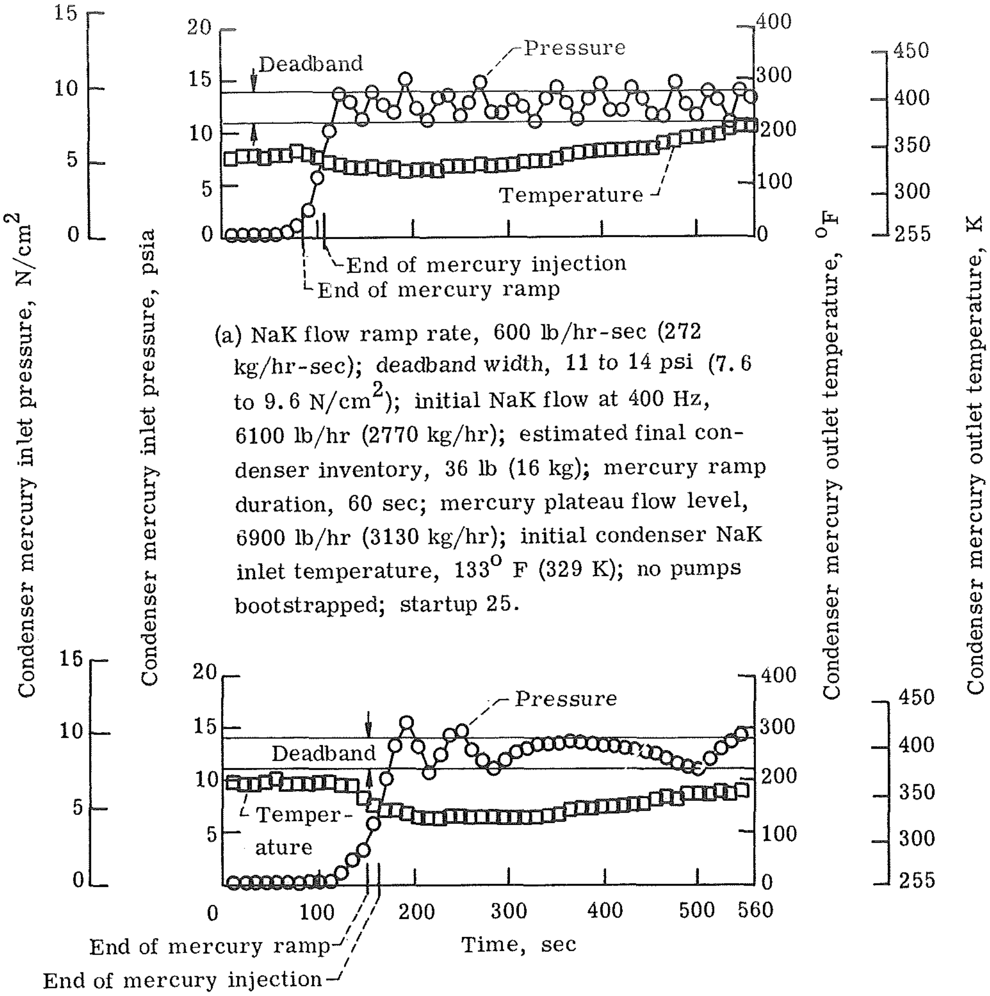
Figure 5. - Condenser inventory as function of condenser pressure rise.



(a) Deadband width, 9.5 to 11.0 psi (6.5 to 7.6 N/cm^2); initial condenser inventory, 63 lb (29 kg); estimated final condenser inventory, 86 lb (39 kg); NaK flow ramp rate, 150 lb/hr-sec (68.0 kg/hr-sec); initial NaK flow at 400 Hz, 6000 lb/hr (2720 kg/hr); mercury ramp duration, 100 sec; mercury plateau flow level, 6900 lb/hr (3140 kg/hr); initial condenser NaK inlet temperature, 115^o F (319 K); all pumps bootstrapped; startup 129.

(b) Deadband width, 12 to 14 psi (8.3 to 9.7 N/cm^2); initial condenser inventory, 43 lb (20 kg); estimated final condenser inventory, 102 lb (46.3 kg); NaK flow ramp rate, 150 lb/hr-sec (68.0 kg/hr-sec); initial NaK flow at 400 Hz, 6000 lb/hr (2720 kg/hr); mercury ramp duration, 100 sec; mercury plateau flow level, 6900 lb/hr (3140 kg/hr); initial condenser NaK inlet temperature, 115^o F (319 K); all pumps bootstrapped; startup 120.

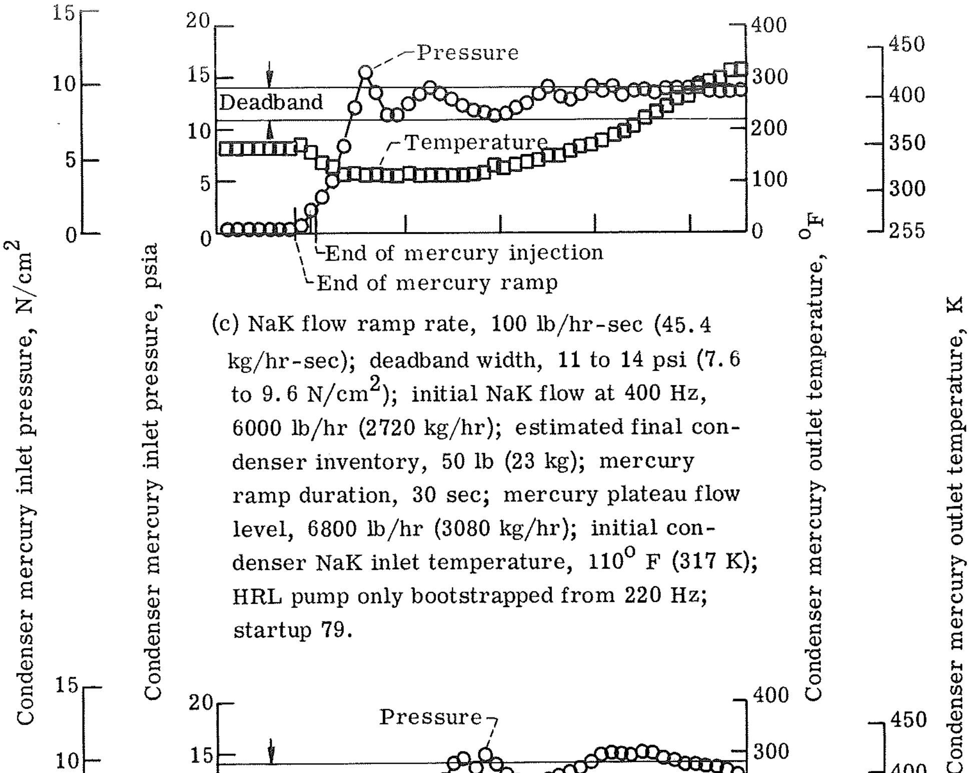
Figure 6. - Effect of deadband width on condenser pressure control.



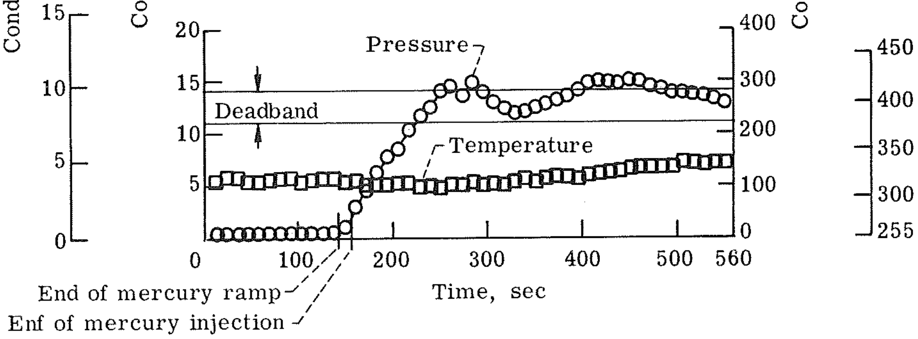
(a) NaK flow ramp rate, 600 lb/hr-sec (272 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow at 400 Hz, 6100 lb/hr (2770 kg/hr); estimated final condenser inventory, 36 lb (16 kg); mercury ramp duration, 60 sec; mercury plateau flow level, 6900 lb/hr (3130 kg/hr); initial condenser NaK inlet temperature, 133^o F (329 K); no pumps bootstrapped; startup 25.

(b) NaK flow ramp rate, 200 lb/hr-sec (90.8 kg/hr-sec; deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow at 400 Hz, 6500 lb/hr (2950 kg/hr); estimated final condenser inventory, 36 lb (16 kg); mercury ramp duration, 60 sec; mercury plateau flow level, 6900 lb/hr (3130 kg/hr); initial condenser NaK inlet temperature, 133^o (329 K); no pumps bootstrapped; startup 27.

Figure 7. - Effect of NaK flow ramp rate on condenser pressure control.

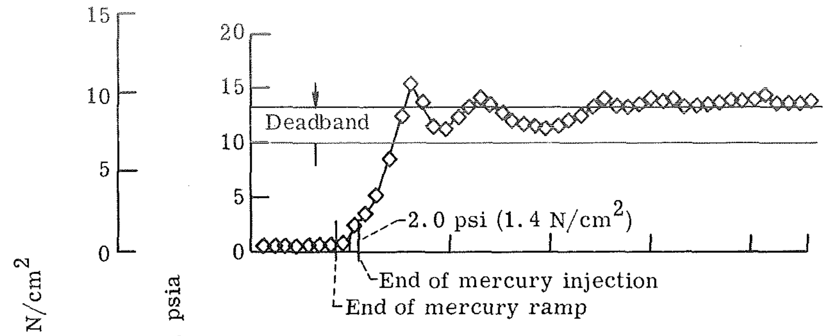


(c) NaK flow ramp rate, 100 lb/hr-sec (45.4 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow at 400 Hz, 6000 lb/hr (2720 kg/hr); estimated final condenser inventory, 50 lb (23 kg); mercury ramp duration, 30 sec; mercury plateau flow level, 6800 lb/hr (3080 kg/hr); initial condenser NaK inlet temperature, 110° F (317 K); HRL pump only bootstrapped from 220 Hz; startup 79.

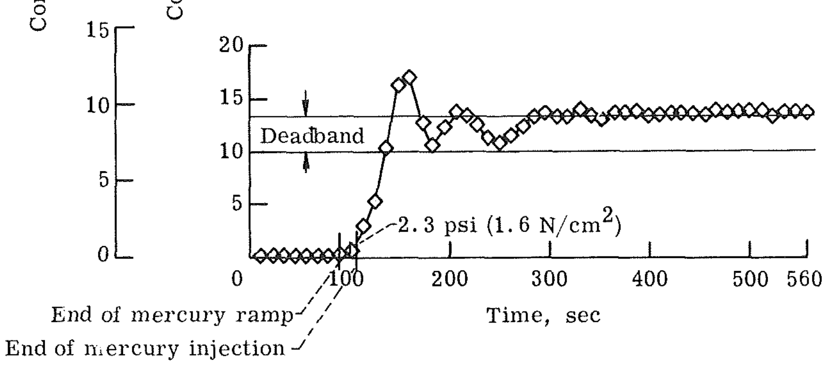


(d) NaK flow ramp rate, 15 lb/hr-sec (6.8 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow at 400 Hz, 7500 lb/hr (3400 kg/hr); estimated final condenser inventory, 68 lb (31 kg); mercury ramp duration, 60 sec; mercury plateau flow level, 6900 lb/hr (3130 kg/hr); initial condenser NaK inlet temperature, 110° F (317 K); all pumps bootstrapped from 220 Hz; startup 111.

Figure 7. - Concluded.

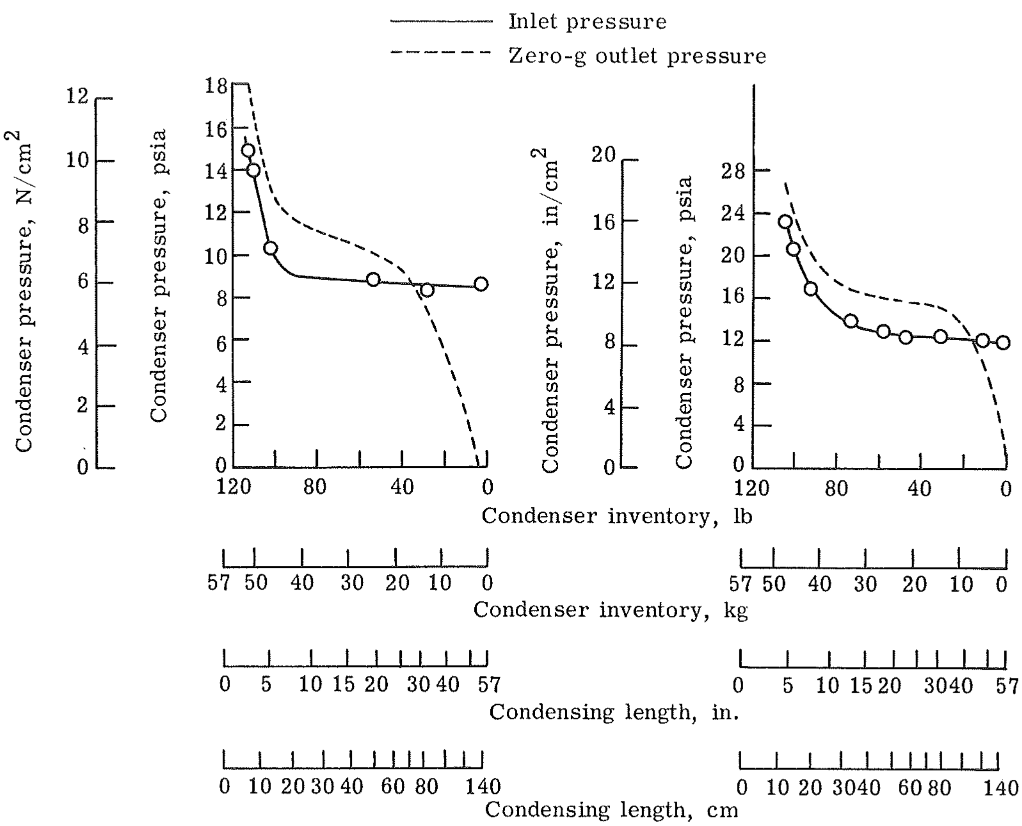


(a) Initial NaK flow rate at 400 Hz, 6200 lb/hr (2820 kg/hr); NaK flow rate at 220 Hz, 4500 lb/hr (2040 kg/hr); NaK flow ramp rate, 100 lb/hr-sec (45.4 kg/hr-sec); deadband width, 10 to 13 psi (6.9 to 9.0 N/cm^2); estimated final condenser inventory, 50 lb (23 kg); mercury ramp duration, 30 sec; mercury plateau flow level, 6800 lb/hr (3080 kg/hr); initial condenser NaK inlet temperature, 110° F (317 K); HRL pump bootstrapped from 220 Hz; startup 79.



(b) Initial NaK flow rate at 400 Hz, 5500 lb/hr (2500 kg/hr); NaK flow rate at 220 Hz, 4250 lb/hr (1930 kg/hr); NaK flow ramp rate, 100 lb/hr-sec (45.4 kg/hr-sec); deadband width, 10 to 13 psi (6.9 to 9.0 N/cm^2); estimated final condenser inventory, 50 lb (23 kg); mercury ramp duration, 30 sec; mercury plateau flow level, 6800 lb/hr (3080 kg/hr); initial condenser NaK inlet temperature, 105° F (314 K); HRL pump bootstrapped from 220 Hz; startup 80.

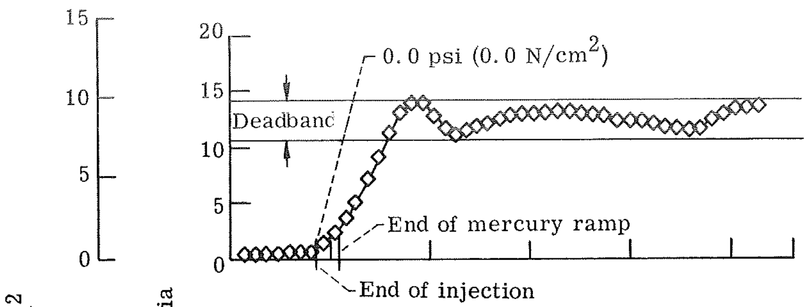
Figure 8. - Effect of initial NaK flow rate on condenser pressure control.



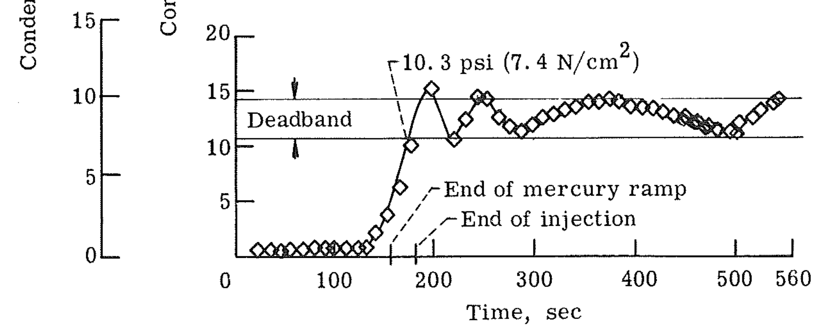
(a) Self-sustaining operation. Condenser mercury flow, 6700 pounds per hour (3040 kg/hr); condenser NaK flow, 12 000 pounds per hour (5450 kg/hr); condenser NaK inlet temperature, 290° F (416 K).

(b) Rated flow operation. Condenser mercury flow, 12 300 pounds per hour (5680 kg/hr); condenser NaK flow, 39 600 pounds per hour (18 000 kg/hr); condenser NaK inlet temperature, 465° F (513 K).

Figure 9. - Condenser inlet and zero-g outlet pressures as functions of condenser inventory.



(a) Estimated final condenser inventory, 16 lb (7.3 kg); NaK flow ramp rate, 200 lb/hr-sec (90.8 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow rate at 400 Hz, 6000 lb/hr (2720 kg/hr); estimated final condenser inventory, 16 lb (7.3 kg); mercury ramp duration, 60 sec; mercury plateau flow level, 6900 lb/hr (3130 kg/hr); initial condenser NaK inlet temperature, 135° F (330 K); no pumps bootstrapped; startup 29.



(b) Estimated final condenser inventory, 36 lb (16 kg); NaK flow ramp rate, 200 lb/hr-sec (90.8 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow rate at 400 Hz, 6000 lb/hr (2720 kg/hr); estimated final condenser inventory, 36 lb (16 kg); mercury ramp duration, 60 sec; mercury plateau flow level, 6900 lb/hr (3130 kg/hr); initial condenser NaK inlet temperature, 135° F (330 K); no pumps bootstrapped; startup 27.

Figure 10. - Effect of condenser inventory on condenser pressure control.

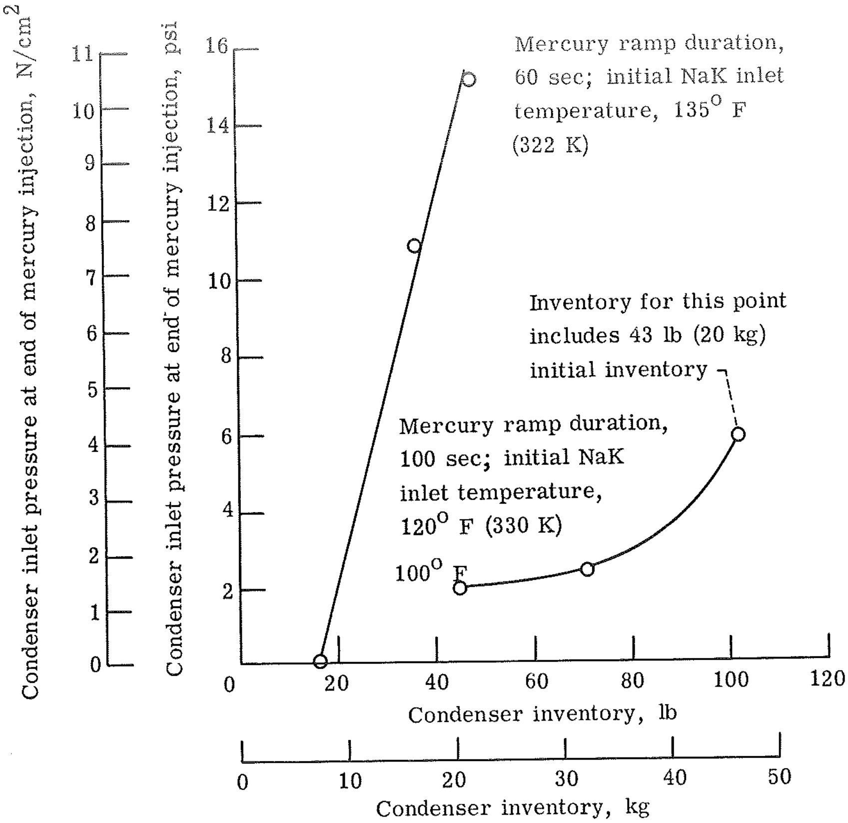


Figure 11. - Condenser inlet pressure at end of mercury injection as function of condenser inventory. Initial NaK flow rate, 6000 pounds per hour (2720 kg/hr).

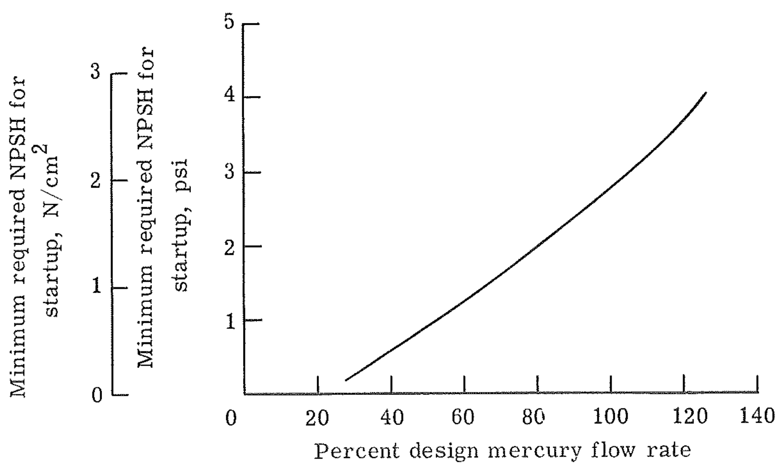
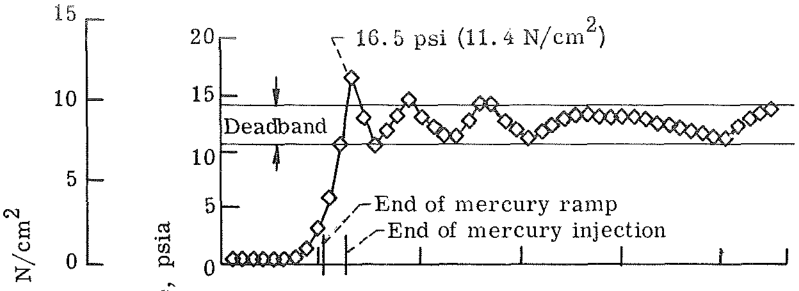
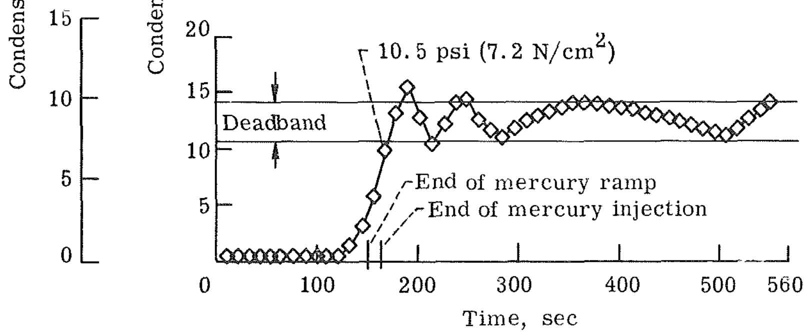


Figure 12. - Minimum required NPSH for startup as function of percent of design mercury flow rate. Design mercury flow, 12 300 pounds per hour (5680 kg/hr).

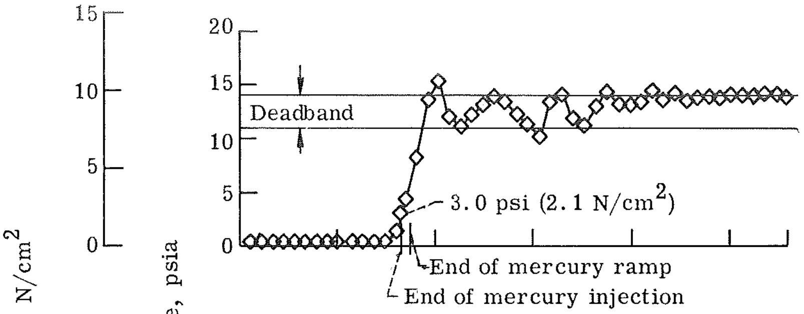


(a) Mercury ramp duration, 30 sec; NaK flow ramp rate, 200 lb/hr-sec (90.8 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow rate at 400 Hz, 6500 lb/hr (2950 kg/hr); estimated final condenser inventory, 44 lb (20 kg); mercury plateau flow level, 6900 lb/hr (3130 kg/hr); initial condenser NaK inlet temperature, 130^o F (328 K); no pumps bootstrapped; startup 30.

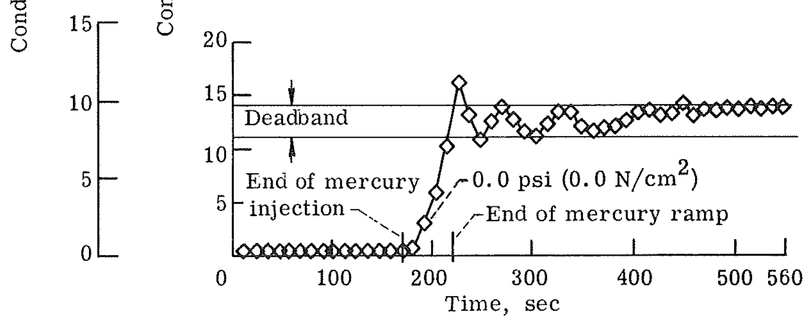


(b) Mercury ramp duration, 60 sec; NaK flow ramp rate, 200 lb/hr-sec (90.8 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow rate at 400 Hz, 6500 lb/hr (2950 kg/hr); estimated final condenser inventory, 36 lb (16 kg); mercury plateau flow level, 6900 lb/hr (3130 kg/hr); initial condenser NaK inlet temperature, 135^o F (330 K); no pumps bootstrapped; startup 27.

Figure 13. - Effect of mercury ramp duration on condenser pressure control.

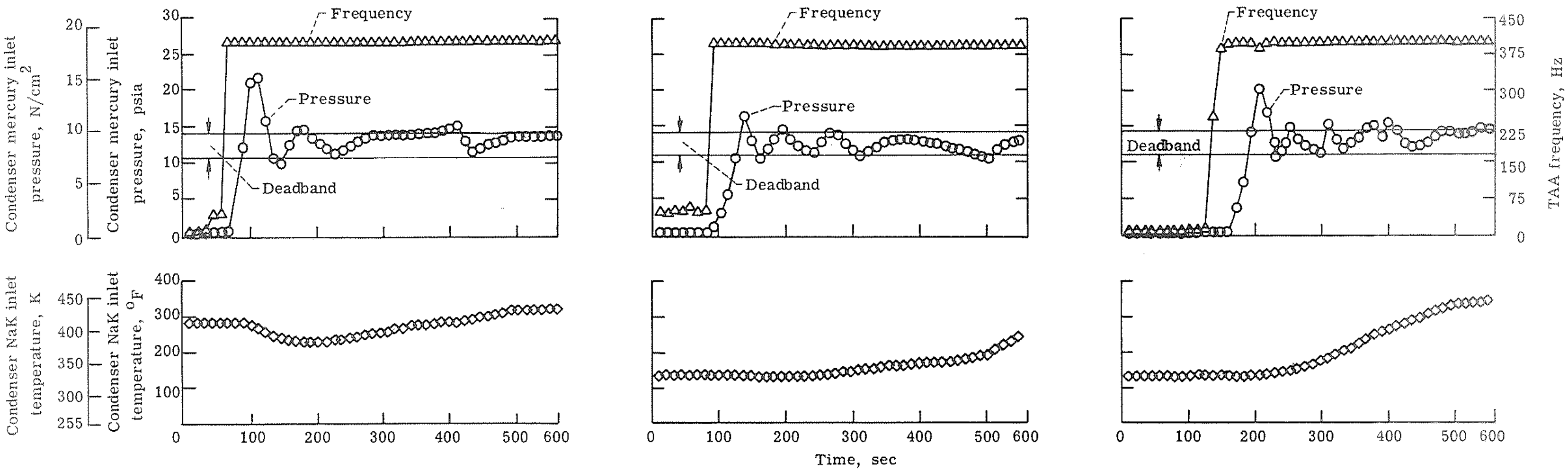


(c) Mercury ramp duration, 100 sec; NaK flow ramp rate, 150 lb/hr-sec (68.0 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow rate at 400 Hz, 6000 lb/hr (2720 kg/hr); NaK flow rate at 290 Hz, 5000 lb/hr (2270 kg/hr); estimated final condenser inventory, 71 lb (32 kg); mercury plateau flow, 6900 lb/hr (3130 kg/hr); initial condenser NaK inlet temperature, 120° F (322 K); all pumps bootstrapped from 290 Hz; startup 119.



(d) Mercury ramp duration, 140 sec; NaK flow ramp rate, 150 lb/hr-sec (68.0 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow rate at 400 Hz, 6000 lb/hr (2720 kg/hr); NaK flow rate at 290 Hz, 5000 lb/hr (2270 kg/hr); estimated final condenser inventory, 76 lb (35 kg); mercury plateau flow, 6900 lb/hr (3130 kg/hr); initial condenser NaK inlet temperature, 120° F (322 K); all pumps bootstrapped from 290 Hz; startup 118.

Figure 13. - Concluded.

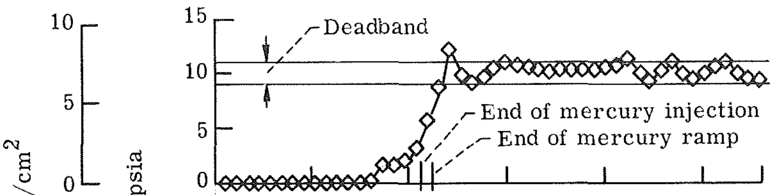


(a) Initial condenser NaK inlet temperature, 285° F (414 K); NaK flow ramp rate, 200 lb/hr-sec (90.8 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow at 400 Hz, 6200 lb/hr (2820 kg/hr); estimated final condenser inventory, 36 lb (16 kg); mercury ramp duration, 30 sec; mercury plateau flow level, 6900 lb/hr (2130 kg/hr); no pumps bootstrapped; startup 31.

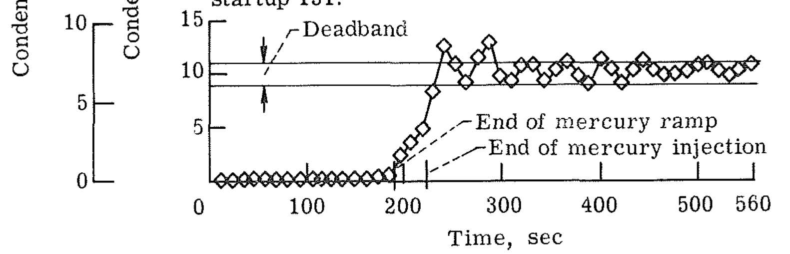
(b) Initial condenser NaK inlet temperature, 130° F (328 K); NaK flow ramp rate, 200 lb/hr-sec (90.8 kg/hr-sec; deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow rate at 400 Hz, 6500 lb/hr (2950 kg/hr); estimated final condenser inventory, 44 lb (20 kg); mercury ramp duration, 30 sec; mercury plateau flow level 6900 lb/hr (3130 kg/hr); no pumps bootstrapped; startup 30.

(c) Initial condenser NaK inlet temperature, 135° F (330 K); NaK flow ramp rate, 200 lb/hr-sec (90.8 kg/hr-sec); deadband width, 11 to 14 psi (7.6 to 9.6 N/cm^2); initial NaK flow rate at 400 Hz, 5000 lb/hr (2270 kg/hr); estimated final condenser inventory, 31 lb (14 kg); mercury ramp duration, 60 sec; mercury plateau flow level, 7100 lb/hr (3220 kg/hr); all pumps bootstrapped from 220 Hz; startup 33.

Figure 14. - Effect of initial NaK inlet temperature of condenser on condenser pressure control.

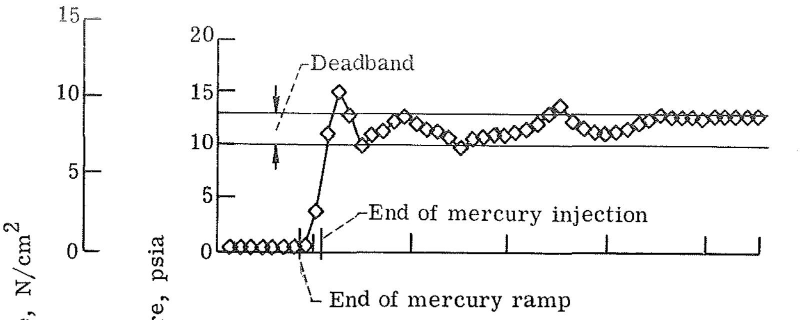


(a) Initial condenser inventory, 2 lb (0.9 kg); NaK flow ramp rate, 150 lb/hr-sec (68.0 kg/hr-sec); deadband width, 9 to 11 psi (6.2 to 7.6 N/cm^2); initial NaK flow rate at 400 Hz, 6000 lb/hr (2720 kg/hr); NaK flow rate at 220 Hz, 4500 lb/hr (2040 kg/hr); estimated final condenser inventory, 45 lb (20 kg); mercury ramp duration, 100 sec; mercury plateau flow level, 7000 lb/hr (3180 kg/hr); initial condenser NaK inlet temperature, 118° F (321 K); all pumps bootstrapped from 200 Hz; startup 131.

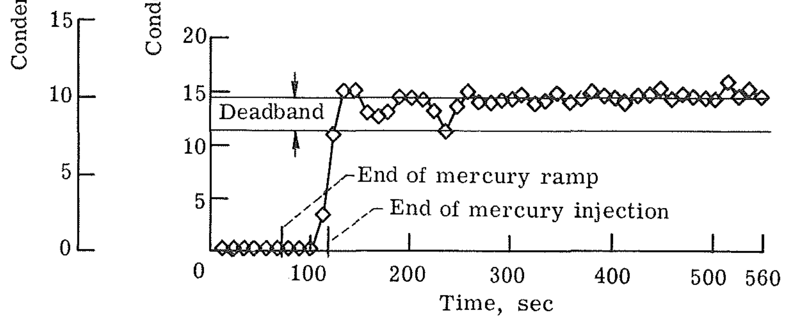


(b) Initial condenser inventory, 43 lb (20 kg); NaK flow ramp rate, 150 lb/hr-sec (68.0 kg/hr-sec); deadband width, 9 to 11 psi (6.2 to 7.6 N/cm^2; initial NaK flow rate at 400 Hz, 6500 lb/hr (2950 kg/hr); NaK flow rate at 240 Hz, 5000 lb/hr (2270 kg/hr); mercury ramp duration, 100 sec; mercury plateau flow level, 7000 lb/hr (3180 kg/hr); initial condenser NaK inlet temperature, 118° F (321 K); all pumps bootstrapped from 240 Hz; startup 126.

Figure 15. - Effect of initial condenser inventory on condenser pressure control.



(a) Deadband width, 10 to 13 psi (6.9 to 9.0 N/cm^2); NaK flow ramp rate, 100 lb/hr-sec (45.4 kg/hr-sec); initial NaK flow rate at 400 Hz, 6000 lb/hr (2720 kg/hr); estimated final condenser inventory, 68 lb (31 kg); mercury ramp duration, 30 sec; mercury plateau flow level, 6800 lb/hr (3080 kg/hr); initial condenser NaK inlet temperature, 115^o (319 K); no pumps bootstrapped; startup 89.



(b) Deadband width, 11.5 to 14.5 psi (7.9 to 10.0 N/cm^2); NaK flow ramp rate, 100 lb/hr-sec (45.4 kg/hr-sec); initial NaK flow rate at 400 Hz, 6500 lb/hr (2950 kg/hr); estimated final condenser inventory, 84 lb (38 kg); mercury ramp duration, 30 sec; mercury plateau flow level, 6800 lb/hr (3080 kg/hr); initial condenser NaK inlet temperature, 110^o F (317 K); no pumps bootstrapped; startup 92.

Figure 16. - Effect of condenser operating pressure level on condenser pressure control.

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